

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
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1. REPORT DATE (DD-MM-YYYY) 01-11-2016		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 13-Sep-2010 - 12-Nov-2015	
4. TITLE AND SUBTITLE Final Report: Predictive Models for Dynamic Brittle Fracture and Damage at High-velocity Impact in Multilayered Targets			5a. CONTRACT NUMBER W911NF-10-1-0431		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 622618		
6. AUTHORS Florin Bobaru			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of Nebraska 151 Whittier Research Center 2200 Vine Street Lincoln, NE 68583 -0861			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 58450-EG.44		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT The goal of this project was to understand the initiation, growth, and propagation of cracks and damage in brittle protective systems induced by impact. For this purpose, we have developed peridynamic models and used them to analyze dynamic fracture in glass, multi-layered glass/PC systems, Functionally Graded Materials (FGMs), polycrystalline AlON, and fiber-reinforced composite (FRC) materials. For the first time we were able to explain why dynamic cracks branch in brittle homogeneous and isotropic materials. We also uncovered the dynamic mechanisms that are behind the development of various crack systems and fragmentation in the impact on multi-					
15. SUBJECT TERMS peridynamics, impact, glass, fracture, fragmentation, crack branching					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Florin Bobaru
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 402-472-8348

Report Title

Final Report: Predictive Models for Dynamic Brittle Fracture and Damage at High-velocity Impact in Multilayered Targets

ABSTRACT

The goal of this project was to understand the initiation, growth, and propagation of cracks and damage in brittle protective systems induced by impact. For this purpose, we have developed peridynamic models and used them to analyze dynamic fracture in glass, multi-layered glass/PC systems, Functionally Graded Materials (FGMs), polycrystalline AlON, and fiber-reinforced composite (FRC) materials. For the first time we were able to explain why dynamic cracks branch in brittle homogeneous and isotropic materials. We also uncovered the dynamic mechanisms that are behind the development of various crack systems and fragmentation in the impact on multi-layers glass. We have also discovered the factors that influence the crack path direction and speed in FGM and FRCs. For the first time, we were able to replicate experimentally observed transition between fragmentation front and localized cracking in AlON. The models developed under this project represent a first step in developing the necessary knowledge for designing brittle protective systems with enhanced performance.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
09/14/2011 1.00	Wenke Hu, Youn Doh Ha, Florin Bobaru. Modeling Dynamic Fracture and Damage in a Fiber-Reinforced Composite Lamina with Peridynamics, International Journal for Multiscale Computational Engineering, (12 2011): 0. doi:
09/14/2011 2.00	Florin Bobaru, Youn Doh Ha. Adaptive refinement and multiscale modeling in 2D Peridynamics, International Journal for Multiscale Computational Engineering, (12 2011): 0. doi:
09/14/2012 7.00	Wenke Hu, Youn Doh Ha, Florin Bobaru, Stewart A. Silling. The formulation and computation of the nonlocal J-integral in bond-based peridynamics, International Journal of Fracture, (07 2012): 195. doi: 10.1007/s10704-012-9745-8
09/14/2012 10.00	Florin Bobaru, Youn Doh Ha, Wenke Hu. Damage progression from impact in layered glass modeled with peridynamics, Central European Journal of Engineering, (12 2012): 0. doi: 10.2478/s13531-012-0020-6
09/14/2012 9.00	Florin Bobaru, Wenke Hu. The Meaning, Selection, and Use of the Peridynamic Horizon and its Relation to Crack Branching in Brittle Materials, International Journal of Fracture, (06 2012): 215. doi: 10.1007/s10704-012-9725-z
09/14/2012 8.00	Wenke Hu, Youn Doh Ha, Florin Bobaru. Peridynamic model for dynamic fracture in unidirectional fiber-reinforced composites, Computer Methods in Applied Mechanics and Engineering, (04 2012): 247. doi: 10.1016/j.cma.2012.01.016
10/03/2013 16.00	Jian Yu, Chian-Fong Yen, Wenke Hu, Yenan Wang, Florin Bobaru. Impact damage on a thin glass plate with a thin polycarbonate backing, International Journal of Impact Engineering, (12 2013): 152. doi: 10.1016/j.ijimpeng.2013.07.001
10/22/2015 29.00	Guanfeng Zhang, Zhanqi Cheng, Yenan Wang, Florin Bobaru. A peridynamic model for dynamic fracture in functionally graded materials, Composite Structures, (12 2015): 529. doi: 10.1016/j.compstruct.2015.07.047
TOTAL:	8

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. G. Zhang, Z. Xu, F. Bobaru. "Peridynamic modeling of mixed trans and intergranular fracture in silicon", International Mechanical Engineering Congress & Exposition. Houston, TX, USA, Nov. 13-19, 2015.
2. G. Zhang, Y. Wang, F. Bobaru. "Peridynamic modeling of mixed trans and intergranular fracture in polycrystalline ceramics", International Mechanical Engineering Congress & Exposition. Houston, TX, USA, Nov. 13-19, 2015.
3. Q. V. Le, F. Bobaru, "Correcting the surface/interface effect in peridynamics: applications to elasticity, fracture, and material interfaces", ASME 2015 International Mechanical Engineering, Houston, TX, Nov. 13-19, 2015.
4. Q. V. Le, F. Bobaru, "Surface and Interface Effects in Peridynamics", Nonlocal Models in Mathematics, Computation, Science, and Engineering Conference, Oak Ridge, TN, Oct. 26-28, 2015.
5. F. Bobaru, G. Zhang. "Transition from damage to localized cracks in dynamic fracture of polycrystalline ceramics", X-DMS 2015 eXtended Discretization MethodS, Ferrara, Italy, Sept. 9-11, 2015.
6. Q. V. Le, F. Bobaru, "Correcting the surface effect in peridynamics: applications to elasticity, fracture, and material interfaces", The 13th US National Congress on Computational Mechanics, San Diego, CA, July 26-30, 2015.
7. Y. Wang, G. Zhang, F. Bobaru, "Evaluation of peridynamic models for damage and failure in fiber reinforced composites", The 13th US National Congress on Computational Mechanics, San Diego, CA, July 26-30, 2015.
8. F. Bobaru and G. Zhang. "Why do cracks branch? A peridynamic investigation", the 2015 International Conference on Computational & Experimental Engineering and Sciences, Reno, Nevada, July 20-24, 2015.
9. F. Bobaru, G. Zhang, On crack branching in dynamic brittle fracture: results from a peridynamic approach,
10. F. Bobaru, G. Zhang. "Peridynamic modeling of crack branching and impact on polycrystalline ceramics", CFRAC 2015, the Fourth International Conference on Computational Modeling of Fracture and Failure of Materials and Structures, Ecole Normale Supérieure de Cachan (Paris), France, June 3-5, 2015.
11. F. Bobaru, Y. Wang, G. Zhang. "Dynamic effects in unidirectional fiber-reinforced composites: a peridynamic analysis", CFRAC 2015, the Fourth International Conference on Computational Modeling of Fracture and Failure of Materials and Structures, Ecole Normale Supérieure de Cachan (Paris), France, June 3-5, 2015.
12. F. Bobaru, Y. Wang, J. Yu, J. Wright, C.F. Yen. "On the morphology of dynamic cracks surfaces and how to resolve them computationally", CFRAC 2015, the Fourth International Conference on Computational Modeling of Fracture and Failure of Materials and Structures, Ecole Normale Supérieure de Cachan (Paris), France, June 3-5, 2015.
13. F. Bobaru, G. Zhang, "Reasons for Using Nonlocal/Peridynamic Models in Dynamic Brittle Fracture". The 17th US National Congress of Theoretical and Applied Mechanics, East Lansing, MI, June 15-20, 2014.
14. F. Bobaru, Y. Wang, J. Yu, C. Yen. "Prediction of roughness in transverse crack surfaces from impact on a glass-polycarbonate two-layer system". The 38th International Conference and Exposition on Advanced Ceramics and Composites, Daytona Beach, FL, Jan. 26-31, 2014.
15. F. Bobaru, Y. Wang, J. Yu, C-F. Yen, "Explaining How Cracks Initiate and Grow in a Thin Glass Plate from Impact: A Peridynamic Analysis". The 17th US National Congress of Theoretical and Applied Mechanics, East Lansing, MI, June 15-20, 2014.
16. F. Bobaru, Y. Wang, "Damage mechanisms and interactions in dynamically loaded fiber-reinforced composites: peridynamic solutions". The ASME 2013 International Mechanical Engineering Congress and Exposition, IMECE 2013, November 15-21, 2013, San Diego, CA, 2013.
17. F. Bobaru, Y. Wang, J. Yu, C-F Yen, "Damage Evolution From Impact On Brittle Multi-layered Targets Modeled With Peridynamics". The ASME 2013 International Mechanical Engineering Congress and Exposition, IMECE 2013, November 15-21, 2013, San Diego, CA, 2013.
18. F. Bobaru, "The Role of Nonlocality in Crack Branching in Brittle Materials". The 12th U.S. National Congress on Computational Mechanics USNCCM12, Raleigh, North Carolina, July 22-25, 2013.
19. F. Bobaru, Y. Wang, "Flux-Corrected Transport for Peridynamics". The 12th U.S. National Congress on Computational Mechanics USNCCM12, Raleigh, North Carolina, July 22-25, 2013.
20. Y. Wang, F. Bobaru, J. Yu, C-F Yen, "Evolution of Damage and Fragmentation Produced by Impact on a Thin Glass-Polycarbonate Plate System". The 12th U.S. National Congress on Computational Mechanics USNCCM12, Raleigh, North Carolina, July 22-25, 2013.
21. F. Bobaru, Y. Wang, "Intersonic Crack Propagation in Fiber-Reinforced Composites: a Peridynamic Approach", SIAM Conference on Mathematical Aspects of Materials Science, Philadelphia, PA, June 9-12, 2013.
22. F. Bobaru, "A Peridynamic Analysis of the Role of Elastic Waves in Controlling Dynamics Brittle Fracture", Workshop on Nonlocal Damage and Failure, San Antonio, Texas, March 11-12, 2013.
23. F. Bobaru, W. Hu, J. Yu, and C.F. Yen, "Brittle fracture evolution in projectile impact on a glass laminate: comparison between experiments and peridynamics results", the 37th International Conference & Exposition on Advanced Ceramics & Composites (ICACC 2013), January 27- February 1st, 2013, Daytona Beach, FL, 2013.
24. F. Bobaru, "Transient heat transfer in bimaterial solids and in bodies with growing cracks", The ASME 2012 International Mechanical Engineering Congress and Exposition, IMECE 2012, November 9-15, 2012, Houston, TX, 2012.
25. W. Hu, S.A. Silling, and F. Bobaru, "Computing The Peridynamic J-Integral", The ASME 2012 International Mechanical Engineering Congress and Exposition, IMECE 2012, November 9-15, 2012, Houston, TX, 2012.
26. F. Bobaru, W. Hu, "Peridynamic modeling of fracture and fragmentation from high-velocity impact on glass plates", The ASME 2012 International Mechanical Engineering Congress and Exposition, IMECE 2012, November 9-15, 2012, Houston, TX, 2012.
27. F. Bobaru, "A nonlocal gradient in nonlinear optimization", The ASME 2012 International Mechanical Engineering Congress and Exposition, IMECE 2012, November 9-15, 2012, Houston, TX, 2012.
28. W. Hu and F. Bobaru, "Peridynamic modeling of intersonic crack propagation in an asymmetrically loaded unidirectional composite", International Workshop on Computational Mechanics of Materials IWCMM XXII, September 24 - 26, 2012, Baltimore, MD.
29. W. Hu, J. Yu, C.F. Yen, F. Bobaru, "Experiments and peridynamic modeling of impact on a thin glass plate with a polycarbonate

backing”, International Workshop on Computational Mechanics of Materials IWCMM XXII, September 24 - 26, 2012, Baltimore, MD.

30. F. Bobaru, W. Hu, “Coarse-grained peridynamic model for high-strain rate dynamic behavior of glassy polymers”, International Workshop on Computational Mechanics of Materials IWCMM XXII, September 24 - 26, 2012, Baltimore, MD.

31. F. Bobaru , “The Importance of the inner problem in computational models of dynamic brittle fracture and why peridynamics works”, The 2012 SIAM Annual Meeting, July 9-13, 2012, Minneapolis, MN, 2012.

32. S.A. Silling, F. Bobaru, and W. Hu, “The Peridynamic J-integral”, The 2012 SIAM Annual Meeting, July 9-13, 2012, Minneapolis, MN, 2012.

33. F. Bobaru, W. Hu, and Y.D. Ha, “Nonlocal models and dynamic fracture: the role of stress waves on crack branching”, The 10th World Congress on Computational Mechanics, 8-13 July, 2012, Sao Paolo, Brazil, 2012.

34. F. Bobaru, Y.D. Ha, and W. Hu, “Peridynamic Modeling of Dynamic Brittle Fracture in a Multi-Layered Glass System”, Society for the Advancement of Material and Process Engineering SAMPE 2012, May 21-24, 2012, Baltimore, MD, 2012.

35. F. Bobaru and Y.D. Ha, “High Velocity Impact Induced Dynamic Brittle Fracture and Damage in Multi-Layered Glass: A Peridynamic Approach”, Proceedings of the ASME 2011 International Mechanical Engineering Congress & Exposition IMECE 2011, November 11-17, 2011, Denver, CO, IMECE2011-64682, 2011.

36. F. Bobaru and W. Hu, “Computing dynamic loading effects on fracture and ultimate failure of fiber-reinforced composites”, Proceedings of the ASME 2011 International Mechanical Engineering Congress & Exposition IMECE 2011, November 11-17, 2011, Denver, CO, IMECE2011-64650, 2011.

37. Y.D. Ha and F. Bobaru, “Dynamic Brittle Fracture captured with Peridynamics”, Proceedings of the ASME 2011 International Mechanical Engineering Congress & Exposition IMECE 2011, November 11-17, 2011, Denver, CO, IMECE2011-65515, 2011.

38. Y.D. Ha, F. Bobaru, “Peridynamic Models for Dynamic Fracture and Damage in Multi-Layered Glass Induced by High Velocity Impact” The 11th U.S. National Congress on Computational Mechanics, Minneapolis, MN, July 25-28, 2011.

39. W. Hu, Y.D. Ha, F. Bobaru, “Dynamic Brittle Fracture and Damage in Unidirectional Fiber-Reinforced Composites with Peridynamics” The 11th U.S. National Congress on Computational Mechanics, Minneapolis, MN, July 25-28, 2011.

Number of Presentations: 39.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>	<u>Paper</u>
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TOTAL:

Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>	<u>Paper</u>
09/14/2011 5.00	Youn Doh Ha, Florin Bobaru. DYNAMIC BRITTLE FRACTURE CAPTURED WITH PERIDYNAMICS, The ASME 2011 International Mechanical Engineering Congress & Exposition IMECE 2011. 11-NOV-11, . : ,
09/14/2012 11.00	Florin Bobaru, Youn Doh Ha. PERIDYNAMIC MODELING OF DYNAMIC BRITTLE FRACTURE IN A MULTI -LAYERED GLASS SYSTEM, Proceedings of the Society for the Advancement of Material and Process Engineering. 22-MAY-12, . : ,
09/14/2012 12.00	Wenke Hu, Youn Doh Ha, Florin Bobaru. Peridynamic models for dynamic fracture in an asymmetrically loaded unidirectional composite, Proceedings of the Computational Structural Engineering Institute of Korea (COSEIK) Annual Conference. 12-APR-12, . : ,
10/17/2014 27.00	Florin Bobaru, Yenan Wang, Jian Yu, Jared Wright, Chian-Fong Yen. How Do Cracks Initiate and Grow in a Thin Glass Plate? A Peridynamic Analysis, U.S. National Congress on Theoretical and Applied Mechanics 2014. 17-JUN-14, . : ,
10/22/2015 30.00	Guanfeng Zhang, Florin Bobaru. Transition from damage to localized cracks in dynamic fracture of polycrystalline ceramics, X-DMS 2015, 9-11 September, Ferrara, Italy. 09-SEP-15, . : ,
10/22/2015 32.00	Florin Bobaru, Yenan Wang, Guanfeng Zhang. Dynamic effects in unidirectional fiber-reinforced composites: a peridynamic analysis, CFRAC 2015. 03-JUN-15, . : ,
TOTAL:	6

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received

Paper

09/14/2011 3.00 Wenke Hu, YounDoh Ha, Florin Bobaru. Peridynamic model for dynamic fracture in unidirectional fiber-reinforced composites, Computer Methods in Applied Mechanics and Engineering (09 2011)

10/17/2014 26.00 Florin Bobaru, Guanfeng Zhang. Crack Branching in Dynamic Brittle Fracture, International Journal of Fracture (10 2014)

10/17/2014 28.00 Zhanqi Cheng, Guanfeng Zhang, Yenan Wang, Florin Bobaru. Dynamic fracture behavior of functionally graded materials based on peridynamics modeling, International Journal of Fracture (11 2014)

TOTAL: 3

Number of Manuscripts:

Books

Received

Book

11/01/2016 38.00 Florin Bobaru, John Foster, Philippe Geubelle, Stewart Silling. , New York, NY: CRC Press, (2016)

TOTAL: 1

Received

Book Chapter

11/01/2016 40.00 Florin Bobaru, Zhanping Xu, Yenan Wang. Peridynamic Modeling of Impact and Fragmentation, Boca Raton, FL: CRC Press, (2016)

11/01/2016 41.00 Florin Bobaru, Guanfeng Zhang. Crack Branching in Dynamic Brittle Fracture, : CRC Press, (2016)

TOTAL: 2

Patents Submitted

Patents Awarded

Awards

1. Florin Bobaru awarded Visiting Scholar at University of Padova, Italy, September 2015.
 2. Florin Bobaru awarded the 2016 College of Engineering Faculty Research and Creative Activity Award.
 3. Florin Bobaru awarded the J.T. Oden Faculty Fellow, Institute for Computational Engineering and Sciences, University of Texas at Austin, Austin, Texas, USA, November 2015.
 4. Guanfeng Zhang (Ph.D. student) awarded summer internships in 2015 and 2016 at GE Global Research Center.
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Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Yenan Wang	0.80	
Wenke Hu	1.00	
Guanfeng Zhang	0.50	
FTE Equivalent:	2.30	
Total Number:	3	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Drew Bakenhus	0.20	Mechanical Engineering
FTE Equivalent:	0.20	
Total Number:	1	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 1.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 1.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 1.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 1.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 1.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Yenan Wang

Wenke Hu

Total Number: 2

Names of other research staff

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Summary of most important results:

1. On the problem of impact damage on glass plates: Post-mortem experimental analysis of the number and types of glass fragments, and their morphology, are well matched by the simulation results from the peridynamic model developed during this project. The model is able to reproduce all of the experimentally observed types of cracks. Fractography on some boundary cracks gives us partial information about the crack growth direction of these cracks. The peridynamic model explains the reason behind this observed behavior. The peridynamic model is able to even capture the equivalent of some fine roughness experimentally observed on the surface of the Hertzian-cone crack, near its end. This is for the first time that a computational model is able to fully predict the complex origin and evolution of fracture and fragmentation in a glass plate from impact, to the finest details.
2. On the dynamic failure of fiber-reinforced composites: The peridynamic model developed in this project is able to predict the observed behavior of FRCs under dynamic loading, including intersonic crack propagation for asymmetrically loaded samples and while using a minimal set of input parameters. The results demonstrate that plastic or viscoplastic effects, if present, are second-order effect as a brittle failure type model is capable of reproducing the experimental results.
3. On dynamic crack branching: we have discovered the reasons for why dynamic cracks branch when the stress intensity is higher than a certain threshold. This resulted in a landmark invited paper in the special issue in IJF dedicated to the 50th Anniversary of International Journal of Fracture.
4. On the J-integral in peridynamics: We have shown that the peridynamic J-integral converges to the classical value, in the limit of the nonlocal horizon going to zero. We have introduced practical steps to be taken in order to compute the peridynamic J-integral. This is critical in our new peridynamic models for fatigue crack growth.
5. A Handbook of Peridynamic Modeling got published this year. Two contributed chapters in this book have been supported directly by this project.

In conclusion, important progress has been made in understanding dynamic brittle fracture, especially dynamic fracture and fragmentation caused by impact. We have demonstrated that it is now possible to predict such behavior and understand its evolution to the finest details. These results are important in designing novel protective systems.

Technology Transfer

Interactions with DOD scientists: one paper published in collaboration with Dr. Chian-Fong Yen (ARL) and Dr. Jian Yu (ARL). One paper submitted in collaboration with Dr. Chian-Fong Yen (ARL), Dr. Jian Yu (ARL), and Jared Wright (formerly of ARL, now at NAVIAR). Collaboration with Dr. George Gazonas (ARL). Dr. Gazonas and Dr. Ray Wildman (ARL) are using algorithms developed by us in modeling material failure at ARL. Dr. Gazonas and Wildman published a book chapter in the Handbook of Peridynamic Modeling, edited by F. Bobaru, J.T. Foster, P. Geubelle, and S.A. Silling.